

SELECTION OF LOCKHEED MARTIN'S PREFERRED TSTO CONFIGURATIONS FOR THE SPACE LAUNCH INITIATIVE

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ABSTRACT

Lockheed Martin is developing concepts for safe, affordable Two Stage to Orbit (TSTO) reusable launch vehicles as part of NASA's Space Launch Initiative. This paper discusses the options considered for the design of the TSTO, the impact of each of these options on the vehicle configuration, the criteria used for selection of preferred configurations, and the results of the selection process. More than twenty configurations were developed in detail in order to compare options such as propellant choice, serial vs. parallel burn sequence, use of propellant crossfeed between stages, "bimese" or optimized stage designs, and high or low staging velocities. Each configuration was analyzed not only for performance and sizing, but also for cost and reliability. The study concluded that kerosene was the superior fuel for first stages, and that bimese vehicles were not attractive.

PROJECT HISTORY

During the late 1990s, Lockheed Martin began using internal funding to study Two Stage to Orbit (TSTO) launch vehicle configurations. Early studies examined the cost and performance of a wide variety of vehicle concepts and concluded that two-stage winged-body launch systems were superior to several alternatives, including various configurations of lifting bodies and vertical landers. Winged-body vehicles provide good packaging efficiency with conventional circular cross-section tanks and avoid the inherent complexity and cost of non-cylindrical conformal tanks. They allow the first stage to fly back to the launch site even when designed with a relatively high staging velocity. Finally, they allow runway landings using a well

understood "wings and wheels" approach. In contrast, lifting body vehicles scored poorly because of their poor packaging efficiency and higher landing speeds. Vertical landers without wings scored poorly because the first stage required substantial quantities of propellant to return to a landing site, and consequently was constrained to low staging velocities. The early trade studies also highlighted the cost and performance benefits of kerosene propellants rather than hydrogen for first stage applications. These early conclusions set the stage for the later work described in this paper.

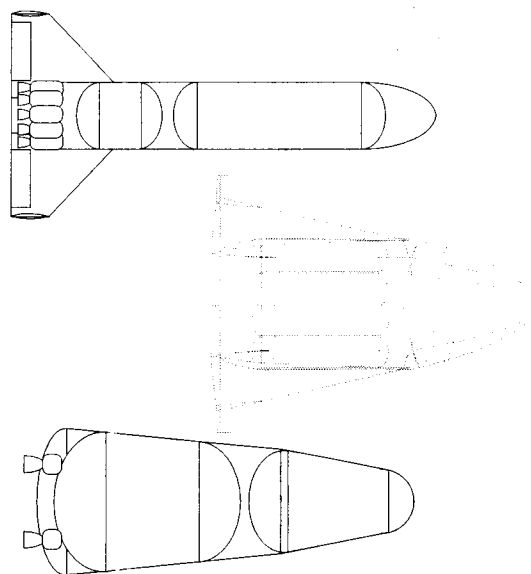


Figure 1. Early Lockheed Martin TSTO stage concepts included several types of winged body shapes (top), lifting bodies (middle), and ballistic shapes (bottom)

SLI PROGRAM BACKGROUND

In 2000, NASA announced the Space Launch Initiative (SLI), a program to develop a Second Generation Reusable Launch Vehicle (2GRLV) to replace the Space Shuttle. The program's key goals are to reduce recurring launch costs to \$1000 per pound of payload and to provide human spaceflight capability that is more than 10 times safer than the Space Shuttle. In the spring of 2001, NASA awarded contracts to 22 companies and universities to develop specific technologies such as engines, thermal protection systems, and structural materials. During 2001 and 2002 the SLI program is focused on development of system requirements and evaluation of potential technologies, rather than on detailed design of a single specific vehicle configuration, which will follow later. However, since the requirements for different technologies and the relative merits of those technologies are dependent on the design of the eventual launch vehicle, it is necessary to develop a conceptual vehicle design that resembles the configuration that will ultimately be built. Therefore, Lockheed Martin received a contract to further study and refine its TSTO concepts for use in the SLI program.

TRADESPACE

During 2001, Lockheed Martin conducted a second trade study to determine more precisely what characteristics its TSTO should have. The trade study considered five key design variables, selected because of their importance in determining basic features of the launch system and the technologies it would need. The variables were:

1) First stage fuel choice

2) Second stage fuel choice

The fuels considered for each stage were kerosene and hydrogen. In both cases the oxidizer was liquid oxygen. The fuel choice determines the ranges of three key performance parameters – specific impulse, engine thrust to weight ratio, and propellant density. Hydrogen engines benefit from higher specific impulse, but kerosene stages have higher thrust to weight and better density. This element of the trade study was considered particularly important because funding for engine development in the SLI program initially focused on developing prototypes of a staged combustion hydrogen engine, with very little funding allocated to kerosene engines. Given the apparent benefits

of kerosene-fueled stages identified in the earlier study, it was important to determine quickly whether the development priorities needed to be changed, or whether hydrogen was, in fact, the superior choice.

3) Stage burn sequence

The options considered were serial burn, parallel burn, or parallel burn with crossfeed. In a serial burn vehicle the stages burn sequentially, with the second stage igniting after the first stage shuts down. A parallel burn vehicle ignites both stages on the ground, with the second stage continuing to operate after first stage separation. This offers the ability to verify all engines are operating prior to liftoff. However, it also carries a performance penalty, because at the time of staging the orbiter tanks are partly empty. A crossfeed system, in which propellants flow from the first stage to the second stage, combines some of the best features of serial and parallel, but the crossfeed hardware is complex, which impacts cost, reliability, and technical risk.

4) Degree of stage commonality

The lowest weight vehicles have a unique first and second stage, each optimized for its specific function. However, significant cost savings might be achieved using the same engine on both stages, or even using identical designs for both stages. The latter option is traditionally referred to as a "bimese" configuration. All three options were considered in this trade.

5) Staging Velocity/First Stage Recovery

A low staging velocity, below Mach 3 to 3.5, allows the first stage to glide back to its launch site. A higher staging velocity reduces overall vehicle size and weight, but requires jet powered return flight for the first stage and exposes it to higher entry temperatures. Two staging velocity values were considered in this trade – one at the limit for glideback vehicles, the other at the higher, optimum staging velocity possible with a jetback system. It should be noted that true bimese vehicles are constrained to a single staging velocity, which results from their stages being the same size. They have no degree of freedom for the staging velocity variable, but their staging velocity happens to correspond roughly to the glideback velocity discussed above.

Each of the five tradespace variables listed above is a discrete, rather than continuous, variable. This greatly simplified the trade, by eliminating the

need to generate utility functions to compare the relative merits of competing continuous variables, and the need to use optimization algorithms to find the best balance of parameters. Instead, it was possible to generate configurations representing every possible combination of the discrete parameter values and score them against each other to pick the best option. There are 72 mathematical combinations of these variables, but not all combinations make physical sense. For example, if a vehicle uses different propellants on the first and second stage, it cannot use the same engine on both stages. Other permutations are physically possible, but do not make engineering sense – for example a vehicle that uses hydrogen for the first stage, but kerosene for the second stage would be inefficient. Removing these combinations left 20 logical configurations to be considered. Each configuration is designated with a five letter code indicating the settings of each variable, as shown in Figure 2.

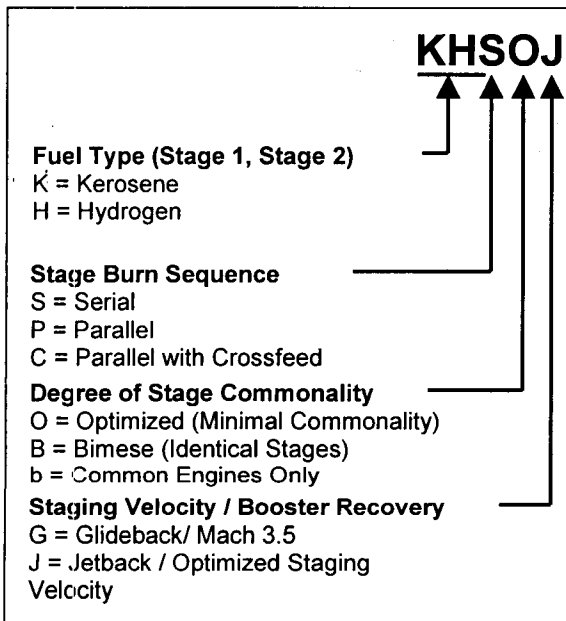


Figure 2. Descriptive code used to name vehicle configurations

FIGURES OF MERIT

The following criteria, grouped in three categories, were specified by NASA as figures of merit for evaluating the TSTO configurations.

Safety/Reliability
Loss of Crew Probability
System Safety

Loss of Vehicle Probability
Loss of Mission Probability
Loss of Payload Probability
Launch Availability

Cost/Economics
Development Cost
Production Cost
Annual Operations Cost
Launch Price

Technical Performance
Technical Risk
Design Margin
Initial Operational Capability Date
NASA Mission Coverage

The priorities applied to the NASA figures of merit were heavily weighted towards safety and cost. Lockheed Martin also developed several additional figures of merit, which reflected commercial priorities. The NASA and Lockheed Martin figures of merit were then broken down into individually weighted subcategories, which were used to compute the scores for the top level figures of merit.

More than three quarters of the total score for these figures of merit was computed quantitatively. For example, the cost of each vehicle configuration was computed and the dollar values could be directly compared. Little of the scoring required subjective "expert opinion." This increased confidence in the accuracy of the results.

VEHICLE SYNTHESIS

In order to draw valid conclusions from a configuration trade study, a sufficiently detailed process must be used to determine the characteristics of each configuration option. Lockheed Martin developed a computer-based multi-disciplinary parametric design environment capable of rapidly generating and analyzing vehicle configurations. The software tools included in this environment are as follows:

Trajectory simulation

Full numerical trajectory simulation is performed using POST II (Program to Optimize Simulated Trajectories) to understand the unique trajectory characteristics and velocity losses associated with each configuration. Simple analysis with the rocket equation is not sufficiently accurate.

Detailed parametric weights and sizing

Dimensions for wings, tanks, and other structures are determined individually from sizing requirements, rather than by photographic scaling of a reference layout. Vehicle weights are computed by estimating the mass of approximately 250 components that make up the vehicle. Parametric mass estimating equations were developed based on extensive research on existing and historical launch vehicles and high performance aircraft, supplemented by design studies of specific subsystems where needed.

Propulsion model

A parametric main engine model was developed for Lockheed Martin by an engine subcontractor. Using input such as desired thrust, throttle setting, and nozzle envelope, the model estimates not only the performance characteristics necessary to size the launch system, such as specific impulse and thrust to weight ratio, but also cost and reliability data needed for scoring different vehicles.

Vehicle convergence

The three tools listed above must be run iteratively to converge on a closed vehicle design in which the launch vehicle sizing, engine performance, and mission trajectory are all compatible. Once the vehicle is developed, the design environment automatically runs various evaluation tools such as a cost model, a reliability model, and a series of trajectories in POST to generate performance curves. The information from these analyses is used to score vehicles against the figures of merit.

During the vehicle design process, special emphasis was focused on design "discriminators" – systems that would be distinctly different on each vehicle configuration, such as engines. However, it is necessary to develop accurate design data for every major subsystem in order to have a complete understanding of the impacts to the vehicle from each design option. For example, one difference between hydrogen and kerosene propellants is that kerosene is approximately 10 times more dense, so kerosene-fueled vehicles can have more compact tanks with lower surface areas. Since the mass of the Thermal Protection System (TPS) is a function of surface area, the choice of propellants has a significant impact on TPS mass. Therefore, an accurate TPS design concept is needed to quantify this effect before the propellant can be accurately chosen, even though the TPS system may seem completely unrelated to the propulsion system. Design refinement was supported by CAD layouts, aerothermal analysis, and wind tunnel testing.

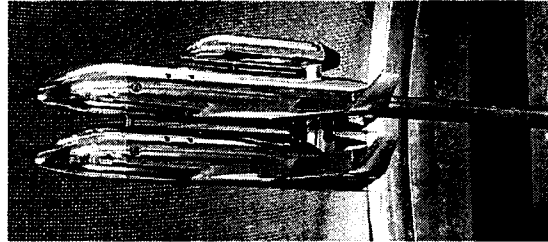


Figure 3. Aerodynamic characteristics were determined with wind tunnel tests, such as the bimese TSTO model shown here.

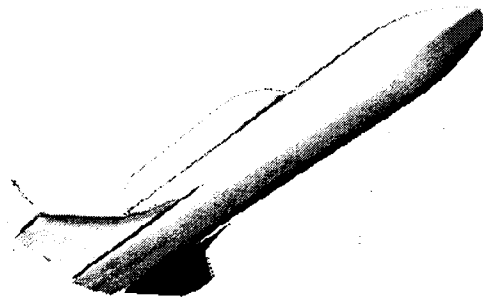


Figure 4. TPS design was based on aerothermal analysis

TRADE STUDY RESULTS

The scores for each vehicle configuration are shown in Figure 5. Several of the configuration options were conclusively ruled out. The bimese vehicle received the lowest score, because the weight and cost penalties associated with duplicating several unnecessary systems on each stage overwhelmed the cost savings of having identical designs. The vehicles with low staging velocities were also clearly inferior. The savings from simplifying the first stage were outweighed by the penalties inherent in a much larger second stage. Glideback vehicles were also very sensitive to weight growth because of their low staging velocity. Vehicles with hydrogen first stages scored poorly, for reasons of cost and safety. Finally, vehicles using propellant crossfeed were found to be inferior because risk and reliability concerns outweighed modest performance benefits.

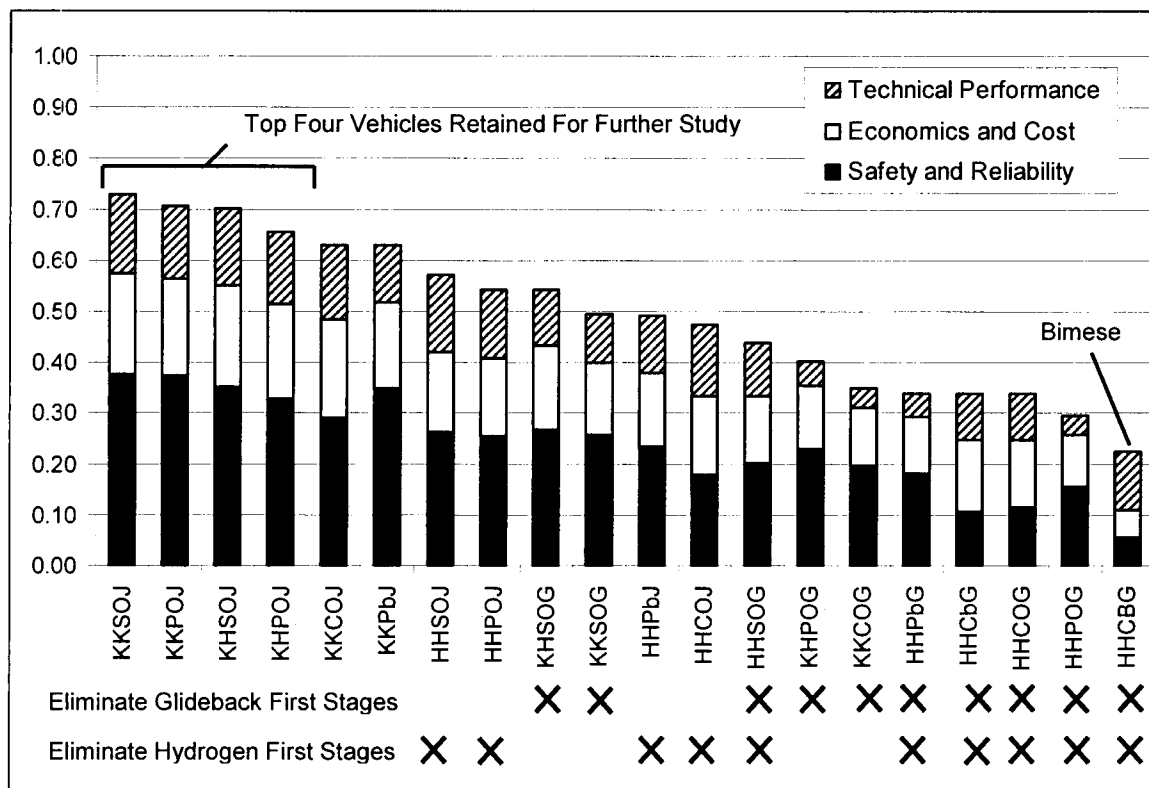


Figure 5: Trade study scores for the 20 vehicles studied. The configurations with glideback first stages were eliminated from consideration first, followed by configurations with hydrogen-fueled first stages.

Based on the results of the trade analysis, the team decided to select the four highest scoring configurations for further study. All four configurations had close scores, and it was felt that further refinement of the vehicle designs would be required before a conclusive decision could be made as to the best of the four. The trade did conclusively determine the best approach for several of the trade parameters, as reflected in the features that all the winning vehicles share in common. Each of the remaining vehicles has a kerosene-fueled first stage, a high staging velocity, and optimized stages with little commonality. The parameters that could not be decided were the second stage fuel, and the choice of a serial or parallel burn sequence. The four remaining vehicles consist of two using kerosene-fueled second stages, and two using hydrogen-fueled stages. In each pair, one vehicle is serial burn, and the other is parallel burn without crossfeed. The four remaining vehicles are shown in Figure 6.

Further analyses and trade studies are being conducted to determine the best propellant choice and stage burn sequence, in order to select a single preferred vehicle configuration by late 2002.

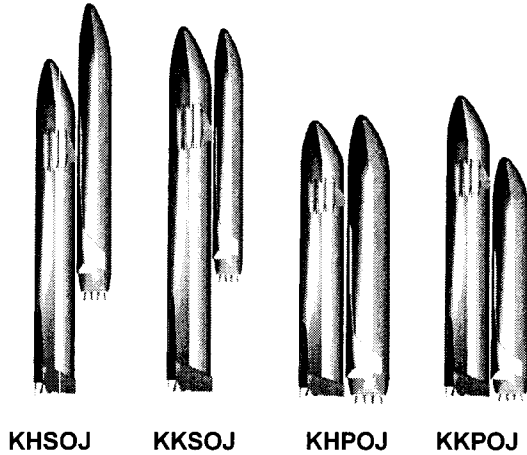


Figure 6: The four highest-scoring TSTO configurations

CONCLUSIONS

Lockheed Martin has completed a preliminary design trade study to select TSTO configurations for further development. The study indicated that kerosene is the preferred propellant for first stages, that high staging velocities result in better launch vehicles, and that optimized stages are superior to a bimane configuration. Further work is under way to select the second stage propellant and stage burn sequence. Several results of the trade study have already influenced the SLI program. For example, as a result of the evidence that kerosene is the superior fuel for first stages, NASA has substantially increased funding for kerosene engine development, and retargeted hydrogen engine studies from a large first stage engine towards a smaller second stage engine.

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Selection of Lockheed Martin's Preferred TSTO Configurations for the Space Launch Initiative

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